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**ERGONOMIC IMPACT OF FASTENING OPERATION
(PREPRINT)**

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Ergonomic Impact of Fastening Operation

A. Joshi¹, M. Leu¹, S. Murray²

Abstract: Fastener installation is a major operation on the assembly shop floor of manufacturing industries. The operator often performs fastening operations at awkward postures depending upon the workplace layout and assembly requirement. These factors combined with the forces involved in the fastening operation put the operator at risk of ergonomics related injuries. In order to design safer workplaces and tools it is necessary to identify the causes of injuries by quantifying the risk factors involved. To quantify the effect of dynamic force, a single-degree-of-freedom dynamic system model is developed to understand the dynamic characteristics of the hand-arm system. The reaction to the impulsive torque generated as a result of fastener shear-off is quantified in terms of the rotation of hand-arm, which is measured using a fixtured experimental setup. Subjects in the experiments were asked to perform fastening operations at different postures using two types of tools: pistol-grip tools and inline tools. The measured data was used to develop a hand-arm dynamic model, which can predict the angular rotation of hand-arm. The angular rotation of the hand-arm is used as an objective measure to assess the dynamic effect of fastening operation with different tools at different postures. The results of the study are used to develop a graphic simulator to display the effects of static and dynamic forces on the operator during a fastening operation. The simulator accepts input parameters related to the work environment such as tool type, posture, and subject population and displays the ergonomic impacts of static and dynamic forces on the operator using RULA and hand-arm rotation, respectively.

Keywords: Fastening, RULA, Hand-Arm Modeling, Ergonomics

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1 Introduction

The operator working in a manufacturing environment is exposed to external forces due to operation of powered hand tools. It is well documented in research studies that workers exposed to external forces develop musculoskeletal injuries commonly referred to as ergonomic injuries. The factors contributing to the causes of ergonomic injuries include:

- External forces (dynamic and static)
- Awkward body postures

The static effects are mainly due to the tool weight and body posture. The dynamic effects are because of the tool vibrations as in case of operations such as drilling and sanding, or dynamic forces or torques as produced in operations such as fastening and riveting. The operator usually counters these forces using awkward postures that are ergonomically unsafe.

In order to improve the operator safety and reduce long-term injuries through good assembly tool/workplace design, it is imperative to quantify the static and dynamic effects for different operator postures. The effect of static force has been well researched and quantified using different metrics. One of such metrics is the Rapid Upper Limb Assessment Tool (RULA) (McAtamney, et. al, 1993). There are a few simulators available commercially that quantify the effect of static force (for example, JACK and Safeworks). However, there is still no commercially available simulator for quantifying the effect of dynamic force. There are a few commercial software systems (for example, MadyMO), which have limited capabilities for dynamic analyses and are mainly used for testing the effects of vehicle crash on the occupants. They have very limited application in assembly/manufacturing operations.

The dynamic effects of powered tool usage can be quantified based on two types of studies, tool vibration and dynamic torque. The tool vibration effects on the human operator can be studied in accordance to the ISO-5349 Standard (2001). However, for many types of powered hand-tools, both electric and pneumatic, the greatest source of dynamic force is a sudden change in the applied torque of the tool. Previous attempts to model the hand-arm response to impulsive torques were based on the response of the hand-arm under conditions of maximum exertion (Lin, et al., 2001; Lin, et al., 2003a; Lin, et al., 2003b).

The purpose of this study is to model the hand-arm as a dynamic system to quantify the effect of dynamic torque exerted on the human operator due to fastening operation. The study then uses this model and the RULA analysis to develop a dynamic simulator to compare the various workplace parameters such as tools and postures that affect the operator safety.

2 Methods

Our study involves quantifying the dynamic effects of fastening operation. The workplace parameters that may affect the operator safety considered in the study are tools and postures. Laboratory experiments are performed to simulate operating conditions and data is collected to quantify the effects due to static and dynamic

forces. The experimental setup to model the operator response to dynamic torque and the tools used are shown in Fig 1.

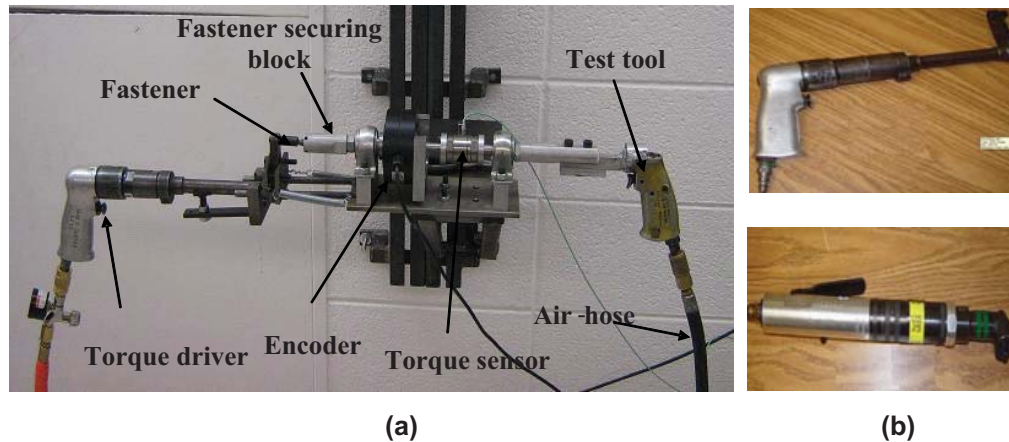


Fig. 1 Experimental setup and tools studied

The experiment consists of installing fasteners on the setup shown in Fig. 1(a). The source of torque input is the torque driver, which is an actual tool as shown on the left side of Fig. 1(a), while the fixtured handle of the test tool shown on the right side is gripped by the test subject to measure the response. The two torque drivers used in the study consist of a pistol-grip tool and an inline tool as shown in Fig. 1(b).

The torque driver is restricted from rotating during the test so that its inertia has no effect on the measured results, but it is allowed to translate along the axis of fastening so that its one end can remain engaged with the fastener until the fastener shears off. The data collection equipment consists of a torque sensor and a rotational encoder. The fasteners are secured using two different tools (pistol-grip and inline) and four different postures. There were five trials for each tool-posture combination.

2.1 Static Analysis

The static analysis is performed using the commercial software package JACK. The workplace environment is simulated in JACK and the effects of static force (tool-weight) and the postures are studied using the Rapid Upper Limb Assessment (RULA) analysis tool. The RULA is a survey method developed to investigate workplaces where upper limb disorders are reported. It assesses the biomechanical and postural loading on the operator.

The inputs for RULA analysis are the static force exerted, which results into the assessment of muscle use and the posture of the operator to determine the comfort level of the operator. In the case of our study, the static force is the result of supporting the tool weight against gravity. The posture of the subject is evaluated by considering the hand-arm, torso, and leg position.

Based on the inputs, the RULA assessment tool provides a discomfort level score in the range from 1-7. Each level defines the action required to be taken for a particular score. The interpretation of the scores and the action taken is as follows:

- Score 1-2 Safe operation position
- Score 3-4 Operation position may possess some risk to the operator, usually a part of the body is in bad position and there is need to correct that position
- Score 5-6 Operator working in poor posture and investigation into the reason of poor posture immediately needed and corrective action be taken to avoid injury
- Score 7 Operator working in the worst posture and corrective actions needs to be taken immediately to avoid any injuries

2.2 Dynamic Analysis

The dynamic analysis we have performed involves analyzing the effects due to tool vibration and dynamic torque exerted at the end of fastening operation.

2.1.1 Tool Vibration Analysis

The effect of tool vibration is studied according to the ISO-5349 Standard. The standard quantifies the effect of tool vibration by an index that predicts the possibility of 10% chance of developing injuries such as finger blanching. To quantify the effects, tool vibration is measured using a tri-axial accelerometer. The experimental setup and the sensors used in the experiment are shown in Fig. 2(a). The accelerometer is attached to the tool handle near the hand-tool interface as shown in Fig. 2(b) and data is collected at a frequency of 5,000 Hz. The measured acceleration is converted to a root mean square (r.m.s) value for analysis purposes. The r.m.s acceleration value is then frequency weighted using a weighting function given in the ISO-5349 Standard.

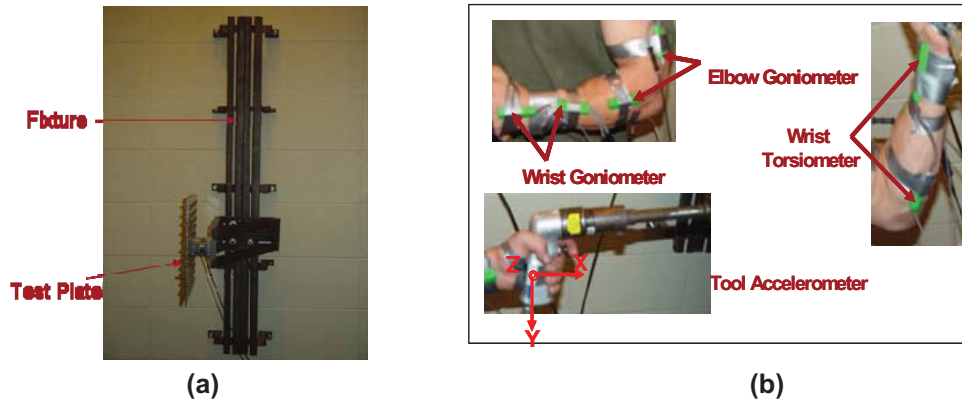


Fig. 2 Experimental setup and sensors used

Assuming that the operator performs the same operation throughout the shift, an 8-hour energy equivalent acceleration is calculated using

$$A(8) = a_{fwrms} \sqrt{\frac{t}{t_0}} \quad (1)$$

where t – total daily exposure to vibration
 t_0 – 8- hour duration
 a_{fwrms} - frequency weighted r.m.s acceleration

This frequency weighted 8-hour energy equivalent acceleration is then used as a measure to assess the effect of tool vibration using

$$(2) \quad Y = 31.8 * A(8)^{-1.06}$$

where Y – no. of years required to develop 10% probability of finger blanching
 $A(8)$ – 8-hour energy equivalent frequency weighted r.m.s acceleration

The results of the study are shown in Table 1. It can be seen from the results that the vibration generated by the two tools is not serious as seen from the number of years required to develop 10% probability of finger blanching.

Table 1. Tool vibration analysis

Tool	Posture	10% Probability of Finger Blanching (years)		
		Subject 1	Subject 2	Subject 3
Pistol	Neutral	18.14	17.51	16.71
	Above Shoulder	23.26	20.90	18.94
	Arm Stretched	18.41	19.47	19.65
	Bent Down	14.12	18.55	32.06
Inline	Neutral Vertical	53.25	65.87	59.43
	Above Shoulder	57.38	45.85	42.30
	Arm Stretched	37.44	43.42	53.25
	Bent Down	37.66	42.86	41.76

2.1.2 Modeling of Hand-Arm System

The hand-arm system is modeled as a single-degree-of-freedom dynamic system to study the effect of dynamic torque exerted on the operator hand-arm. The dynamic torque results from the fastener shearing off at the end of the operation. Modeling of hand-arm system involves a two-step process. The first step models the test tool fixture as a two-degree-of-freedom dynamic system. The second step involves modeling the hand-arm system. The coupled dynamic system of hand-arm and the test tool fixture is shown in Fig 3. The dynamic effect of the tool fixture is subtracted from the coupled system to get the response of the single-degree-of-

freedom system of the hand-arm. The modeling process and parameter estimation methodology is derived from the authors' previous research work (Joshi, et. al. 2008).

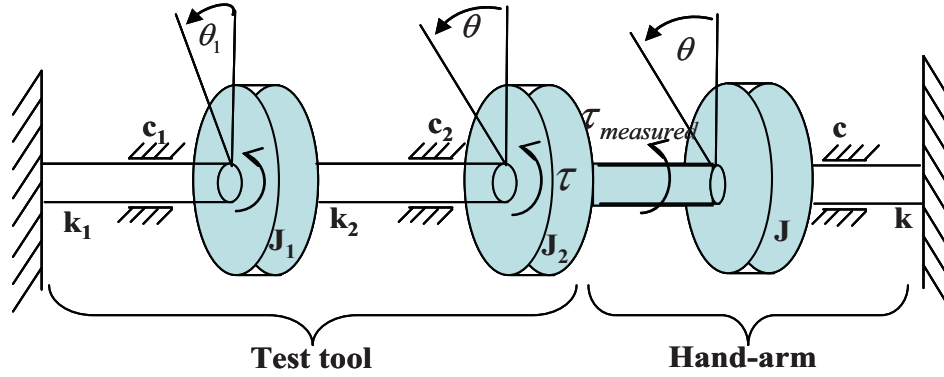


Fig. 3 Coupled tool and hand-arm dynamic system

The results of the hand-arm modeling for one of the subjects and four postures for pistol-grip tool and inline tool are shown in Table 2. The values of the model parameters and the angular rotation of the tool provided in Table 2 are the average of five trials conducted for each tool-posture combination. The hand-arm rotation is used to assess the effect of the dynamic force (torque) on the operator hand-arm. The angular rotation of the hand-arm system can be used as an objective function indicator of the discomfort level of the operators as shown in a previous study (Kihlberg, et al., 1993). It can be further used as a metric to compare different tools and fasteners as well as different postures for various subject populations. This would be helpful to design of tools, fasteners and workplaces for minimizing hand-arm rotation, thus reducing the potential ergonomic risks involved.

3 Ergonomic Fastening Simulator

The ergonomic fastening simulator is designed to simulate the fastening operation as well as provide the ergonomic effect of the fastening operation on the operator. The simulator is developed using Visual Basics in a .Net environment. The Graphic User Interface (GUI) of the simulator has two parts. The simulation part is displayed as a static image of the work environment along with the operator. The analysis portion displays the static as well as dynamic effects of forces exerted on the operator by the fastening tool as well as the posture taken by the operator. The static and dynamic effects are quantified by different metrics explained in Section 2. The metrics and experimentally measured parameters are stored in a database created in Microsoft Access. The simulator essentially operates as a data query and retrieval system.

Table 2. Hand-arm model parameters for pistol grip tool for one subject and four postures

Tool	Posture	Subject 1			
		J	C	K	Tool Rotation
		(kg-m ²)	N-m-s/rad	(N-m/rad)	(degree)
Pistol	Neutral	0.03	0.06	5.56	5.85
	Above Shoulder	0.08	0.18	19.95	5.06
	Arm Stretched	0.04	0.08	6.68	5.41
	Bent	0.04	0.09	9.03	5.53
Inline	Neutral	0.19	0.45	73.31	14.55
	Above Shoulder	0.42	0.79	141.71	8.97
	Arm Stretched	0.26	0.57	123.31	8.86
	Bent	0.26	0.65	39.39	11.13

The inputs of the simulator define the work environment parameters. The simulator has two types of inputs to define the work environment and the operator. The first set of inputs define the tool and the fastener used. The second set of inputs defines the operator parameters. The user can define the gender, percentile population and the posture in which the operator works. A graphic image of the work environment is displayed in the simulator.

The outputs of the simulator depict the effect of the static and dynamic forces on the operator. The outputs of the simulator have three sections. The first section provides the angular rotation measurements of the wrist and forearm. These measurements are made by sensors attached to the subject hand-arm during experimentation as shown in Fig. 2(b). The second section gives the model parameter values of the hand-arm model. The third section provides the dynamic effects of the fastening operation. The effect of tool vibration is provided in terms of number of years taken to develop a 10% probability of finger blanching. The effect of dynamic torque is provided in terms of the tool handle displacement based on the study by Kihlberg (1993). The tool handle displacement is computed by multiplying the tool length by the angular rotation of the tool as measured by the encoder in Fig. 1. The static effects are quantified using the RULA score.

The text boxes for the RULA and the hand-arm displacement score are color-coded. A 'green' box indicates safe operation whereas a 'yellow' box indicates caution. A 'red' box indicates that the operation is not safe for that posture and tool combination. At the bottom left corner of the simulator, text boxes are provided to give instructions to the user.

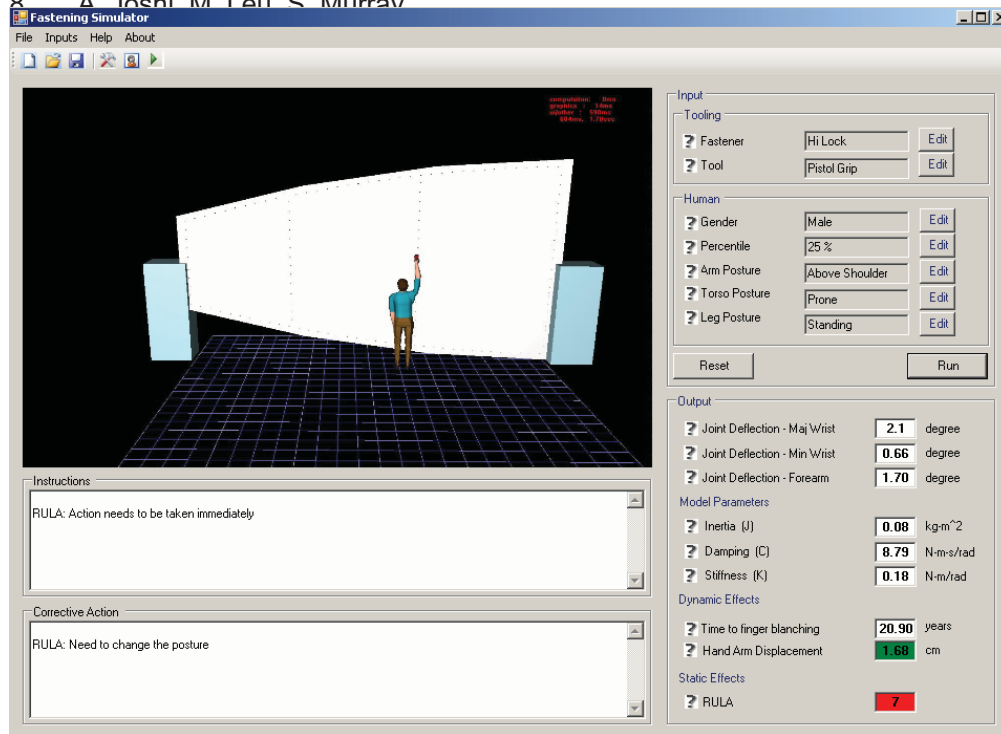


Fig. 4 Screenshot of the ergonomic fastening simulator

4 Discussion

Assembly operations usually involve the use of powered hand-tools. The operators have to perform the operation at awkward postures depending upon the fixtures and setup conditions. This results in external forces acting on the operator body. To counter the forces the operator usually positions himself/herself so as to achieve a static and dynamic equilibrium. Usually this means that the operator will be in susceptible position to get injured if he/she continues to work in similar fashion. Hence, it is necessary to quantify the effects of external forces on the operator.

Performing ergonomic experiments on the shop floor is a very costly exercise as the sensors required to collect data usually do not last long in the rough environment. Hence, these experiments are carried out in a controlled environment using simulated setups that can reproduce the actual working conditions as on the shop floor. The experiment performed in this study simulates the fastening operation and is able to replicate the forces produced by actual tools.

There are commercially available simulators that depict the effect of static forces on the operator. However, the effect of dynamic forces is also an important factor to be considered in designing a safe work environment for the operator. This is especially important when selecting the tools used for performing the assembly operations. It is a well-known fact that dynamic forces originating from tools lead to musculoskeletal injuries when used for long duration. Hence, a simulator that can depict both the effects of static force and dynamic force would be a very useful tool for design engineers as well as workplace designers. This would ensure that operator safety gets incorporated in the design phase rather than down the line in

product development process, thus saving the expenses required to modify the work environment setups later.

The ergonomic fastening simulator developed in this study takes into account the various work environment parameters such as tool and posture. The operator safety is based on the RULA and the hand-arm displacement. The RULA covers static force effects while the hand-arm displacement covers the effect of dynamic forces for fastening operation.

Our study uses the hand-arm displacement as an objective measure to quantify the dynamic effect due to the torque exerted as a result of fastener shear-off. Kihlberg et. al. (1993) used a study of tool handle displacement to put forth acceptable limits on the handle displacement in neutral posture. In this study we assume that the same acceptability limits can be applied to all the postures of the hand-arm. This assumption is important because as seen from the results of experimental measurements, postures away from neutral have smaller hand-arm displacements and thus are better in terms of dynamic force. This is in contrast to the generally accepted notion that postures close to neutral are beneficial to the operator, which is true in case of static forces. This is an open area of research where more epidemiological studies are required to quantify the effect due to the dynamic force. Currently, there is little data available in the literature that can support or contradict the assumption made. Future studies are required to create acceptable limits for dynamic forces at different postures.

The developed simulator has the capability of comparing different work environment parameters such as tools, postures, and subject populations. It can also be used to test tools with different torque profiles based on the hand-arm model to determine the effect they have on the hand-arm displacement.

5 Conclusion

The static and dynamic effects of using the powered hand-tools as well as effects due to posture variations are considered. The RULA is used to assess the effect of static force. A single degree-of-freedom dynamic system for the hand-arm system is proposed to study the effect of dynamic torque exerted on the operator at the end of fastening operation. Based on the results we have developed a simulator that can simulate the work environment along with the operator and provide the ergonomic impact of performing fastening operation on the operator. The inputs of the simulator define the work environment parameters. The outputs of the simulator depict the effect of the static and dynamic forces on the operator. The effect of tool vibration is provided in terms of number of years taken to develop a 10% probability of finger blanching. The effect of dynamic torque is provided in terms of the tool handle displacement, which is computed by multiplying the tool length by the angular rotation of the tool. The static effects are quantified using the RULA score.

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